An evaluation of the possibility of tectonic triggering of the Sinabung eruption

Kriswati, Estu; Meilano, Irwan; Iguchi, Masato; Abidin, H.Z.; Surono

Journal of Volcanology and Geothermal Research xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

An evaluation of the possibility of tectonic triggering of the Sinabung eruption

Estu Kriswati [a,*], Irwan Meilano [b], Masato Iguchi [c], H.Z. Abidin [b], Surono [a]

[a] *Centre for Volcanology and Geological Hazard Mitigation, Geological Agency, Indonesia*
[b] *Geodesy Research Group, Faculty of Earth Science and Technology, Institute of Technology Bandung, Indonesia*
[c] *Sakurajima Volcano Research Center, Kyoto University, Japan*

ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form 26 March 2018
Accepted 30 April 2018
Available online xxxx

Keywords:
Strain
Sinabung
Volcano deformation
Seismicity
Volcano-tectonics interaction

ABSTRACT

The aim of this work is to determine if tectonic seismicity may have had a role in triggering volcanic activity at Sinabung volcano and to evaluate the relative importance of different seismic parameters that could contribute to triggering an eruption. We focus on the potential role of static strain, including the timing and magnitude of changes in volumetric strain and the direction of principal strain to investigate the relation between tectonic strain changes and variations in volcanic activity at Sinabung volcano.

Sinabung erupted first in August and September 2010, and then following three years of quiescence, a seismic swarm at the volcano began on 4 July 2013, two days after the Bireun earthquake (M_w 6.1), which was located 252 km from the volcano. Subsequent to these events a new series of eruptions started on 15 September 2013 and continues through today. Ground deformation, as measured with GPS, showed significant changes at Sinabung during the 4 months following the Bireun earthquake and before the September 15 eruption, reaching 8–11 mm of horizontal displacement.

To evaluate the possibility of seismic triggering of activity at Sinabung, we used Global CMT solutions of large tectonic earthquakes within 1000 km of the volcano to estimate strain changes and compared these changes to the timing of volcanic activity and seismicity and to ground deformation. We find no unequivocal relationship between changes in the volumetric strain from the regional tectonic earthquakes and timing of volcanic activity at Sinabung. However, we find that the orientation of the extensional component of the strain produced by the Bireun earthquake is perpendicular to the strike of a mapped fault the crosses the volcano. We suggest that because the Sinabung magmatic system was already pressurized, this small change in extensional strain across this fault zone could have initiated the magma ascent and the consequent seismic swarm that led to the 2013 eruption.

1. Introduction

The Sumatra region is characterized by a large number of earthquakes at the boundaries between the subducting Indo-Australia plate, the Sumatra fault zone and several active volcanoes that are lined up along this fault zone. It has been suggested that some volcanoes in Sumatra have shown increases in volcanic activity possibly related to tectonic earthquakes. For example, an increase in volcanic seismicity at Kaba volcano was recorded following the M 7.8 Bengkulu earthquake on 4 June 2000 (http://vsi.esdm.go.id/index.php/gunungapi/data-dasar-gunungapi/501-g-kaba). The eruption of Talang volcano in West Sumatra on 12 April 2005 occurred only 2 days after the Mentawai earthquake (Purbawinata, 2005). Seismicity and fumarolic activity at Talang increased on 1 October 2009 immediately after the Southern Sumatran earthquake on the same day (Kriswati et al., 2012).

Sinabung volcano, North Sumatra, began to erupt in August 2010 and entered into a renewed phase of activity in September 2013. At the time of this writing (mid 2017), the eruption still continues, generating pyroclastic flows and lahars. Sinabung is located only 25 km away from the Sumatran fault zone and <300 km from the subduction trench (Fig. 1). Because of proximity to these major tectonic structures, we want to understand if strain changes related to earthquakes along these structures have played any role in triggering volcanic seismicity or eruptions at Sinabung.

Research on the interaction between volcanism and tectonics has been the subject of increased attention in recent years. Two principal models of stress change have been proposed to explain increases in volcanic activity following tectonic earthquakes: static stress change triggering (King et al., 1994; Stein, 1999) and dynamic stress change triggering (Hill and Prejean, 2007; Fuchs, 2014), due to processes such

* Corresponding author at: Centre for Volcanology and Geological Hazard Mitigation, Geological Agency, Indonesia.
E-mail address: estu@vsi.esdm.go.id (E. Kriswati).

https://doi.org/10.1016/j.jvolgeores.2018.04.031
0377-0273/

Please cite this article as: Kriswati, E., et al., An evaluation of the possibility of tectonic triggering of the Sinabung eruption, J. Volcanol. Geotherm. Res. (2018), https://doi.org/10.1016/j.jvolgeores.2018.04.031

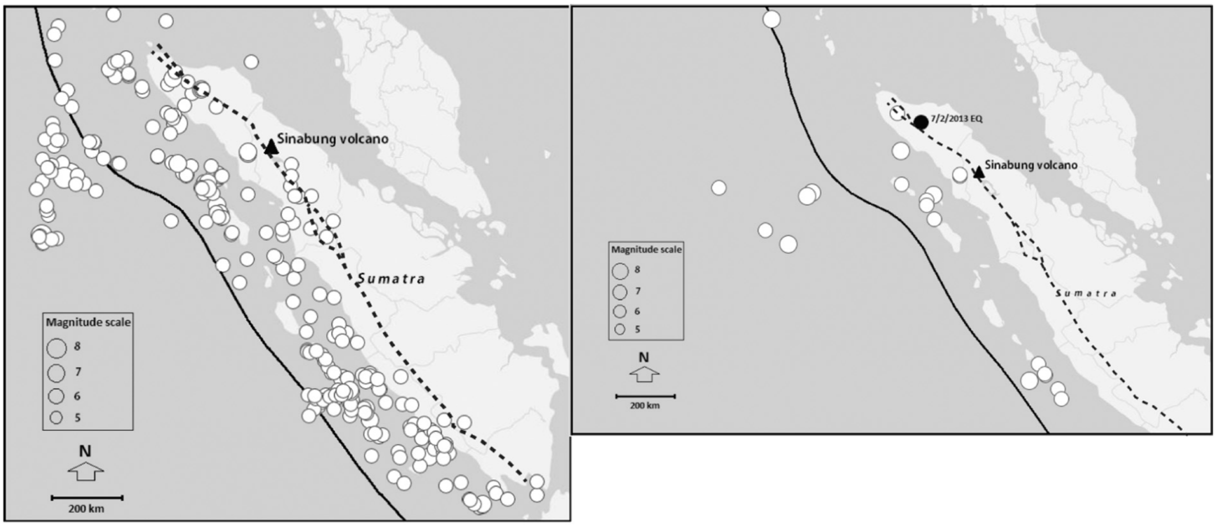


Fig. 1. Seismicity and tectonic setting around Sinabung volcano. Triangle shows the location of Sinabung volcano. The solid line shows the location of the subduction trench and the dashed line is Sumatran fault. (Left) Epicenters of earthquakes with magnitude of 5.0–8.6 in the period 2010–2013. (Right) Epicenters of 21 earthquakes of Mw ≥ 6 that occurred within 1000 km of Sinabung volcano during the period of 2010–2013, and black circle is the 7/2/2013 Bireun earthquake (map source: earthquake.usgs.gov/earthquakes).

as advective overpressure and rectified diffusion (Manga and Brodsky, 2006), relaxation of a magma body (Hill et al., 1995), sinking crystal plumes (Hill et al., 2002; Manga and Brodsky, 2006), hydraulic surge (Fournier, 1999), and fatigue and subcritical crack growth (Dobran, 2001). Hill et al. (2002) proposed that earthquake–volcano interactions due to static stress changes are controlled by pressure changes in a magma body. These pressure changes are thought to be induced by the isotropic, compressional component of the stress field in the vicinity of the volcano. Hill et al. (2002) studied a series of proposed earthquake triggered volcanic eruptions (e.g., the 1707 eruption at Mt. Fuji, Japan after an earthquake of M 8.2, and the 1991 eruption of Mt. Pinatubo in the Philippines following a M 7.7 earthquake in 1990). They concluded that increased compressional stress in the crust surrounding a magma chamber, close to its critical state, may squeeze magma upward (as previously suggested by Nakamura, 1975 and Nostro et al., 1998); on the other hand, a decrease in compressional stress can promote additional melting, the formation of bubbles as volatiles exsolve and the "unclamping" of conduits above the magma chamber (c.f., Bursik, 2009; Walter and Amelung, 2006), or magma ascent could be aided by fluctuations between compression and extension during passing of seismic waves (Walter and Amelung, 2007).

The tectonic triggering of eruptions is an intriguing possibility and has been suggested in oral presentations by some local workers for the Sinabung eruption. However, the global evidence in favor of eruption triggering is extremely limited (e.g., Manga and Brodsky, 2006 and White and Harlow, 1993) and the data in this paper bears this out with respect to candidate earthquakes in the region. Triggering of volcanic eruption by tectonic earthquakes depends on parameters such as focal mechanism, magnitude, epicentral distance, and the initial state of the magmatic system prior to the earthquake. The aim of this work is to determine if tectonic seismicity may have had a role in triggering volcanic activity at Sinabung and to infer the relative importance of the different parameters in triggering an eruption there. We focus our attention on calculating volumetric strain, determining the spatial

Table 1
List of tectonic earthquakes of Mw ≥ 6 within 1000 km of Sinabung volcano. These 21 events are located in Indonesia, unless noted otherwise.

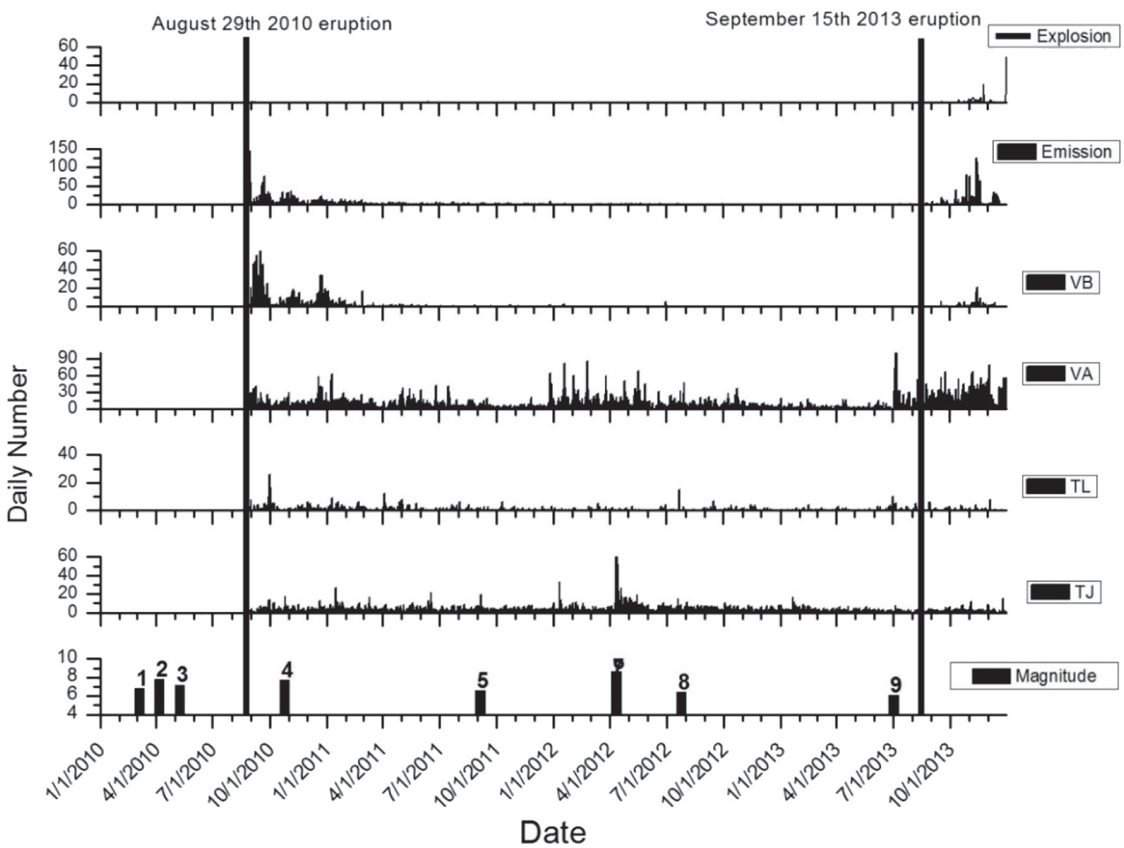
No.	Location	Date	Time (UTC)	Mw	Latitude (°)	Longitude (°)	Depth (km)	Mechanism	Distance from Sinabung (km)
1	Kepulauan Mentawai	3/5/2010	16:07:00	6.8	−3.762	100.991	26.0	Thrust	823
2	Northern Sumatra	4/6/2010	22:15:01	7.8	2.383	97.048	31.0	Thrust	173
3	Southern Sumatra	5/5/2010	16:29:03	6.5	−4.054	101.096	27.0	Thrust	858
4	Northern Sumatra	5/9/2010/	5:59:41	7.2	3.748	96.018	38.0	Thrust	271
5	Nicobar Islands, India	6/12/2010	19:26:50	7.5	7.881	91.936	35.0	Strike slip	886
	Eruption at Sinabung	8/29/2010							
6	Kepulauan Mentawai	10/25/2010	19:37:31	6.3	−2.958	100.372	26.0	Thrust	716
7	Kepulauan Mentawai	10/25/2010	14:42:22	7.8	−3.487	100.082	20.1	Thrust	764
8	Simeulue	*1/26/2011*	15:42:29	6.1	2.205	96.829	23.0	Thrust	204
9	Nias	4/6/2011	14:01:42	6.0	1.612	97.086	20.0	Thrust	226
10	Northern Sumatra	9/5/2011	17:55:11	6.7	2.965	97.893	91.0	Normal	60
11	off the W coast of N Sumatra	1/10/2012	18:36:59	7.2	2.433	93.210	19.0	Strike slip	581
12	off the W coast of N Sumatra	4/11/2012	10:43:10	8.2	0.802	92.463	25.1	Strike slip	710
13	off the W coast of N Sumatra	4/11/2012	8:38:36	8.6	2.327	93.063	20.0	Strike slip	599
14	off the W coast of N Sumatra	*4/15/2012*	5:57:40	6.2	2.581	90.269	25.0	Strike slip	905
15	Northern Sumatra	*6/23/2012*	4:34:53	6.1	3.009	97.896	95.0	Normal	58
16	Simeulue	*7/25/2012*	0:27:45	6.4	2.707	96.045	22.0	Thrust	266
17	Kepulauan Mentawai	*9/14/2012*	4:51:47	6.2	−3.319	100.594	19.0	Thrust	762
18	47 km SSW of Sigli	*1/21/2013*	22:22:52	6.1	4.927	95.907	12.0	Strike slip	338
19	55 km S of Bireun	7/2/2013	7:37:02	6.1	4.645	96.665	13.0	Strike slip	252
20	157 km SW of Sungai Penuh	7/6/2013	5:05:06	6.0	−3.269	100.564	21.0	Thrust	756
	Eruption at Sinabung	9/15/2013							
21	69 km SE of Sinabung	12/1/2013	6:29:57	6.0	2.044	96.826	20.0	Thrust	214

Please cite this article as: Kriswati, E., et al., An evaluation of the possibility of tectonic triggering of the Sinabung eruption, J. Volcanol. Geotherm. Res. (2018), https://doi.org/10.1016/j.jvolgeores.2018.04.031

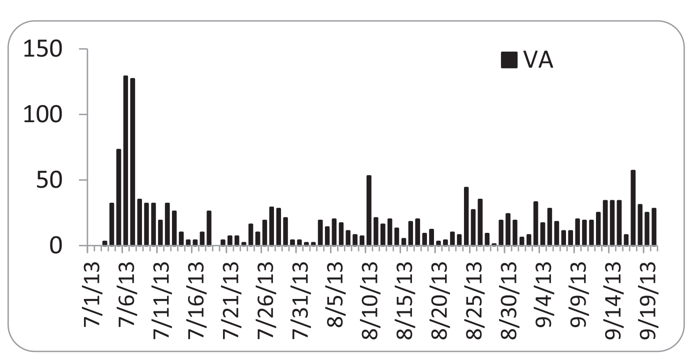
distribution and direction of principal strain, and analyzing volcano deformation and seismicity to infer a possible relation between tectonic strain and volcanic activity.

2. Volcanic activity at Sinabung

Sinabung volcano erupted several times between 29 August and 7 September 2010. No monitoring system was installed before the eruption, so we do not know if either deformation or seismicity preceded the 2010 eruption. However, following the installation of a monitoring network and three years of relative quiescence marked only by occasional swarms of volcanic earthquakes, Sinabung began experiencing a much larger volcanic earthquake swarm on 4 July 2013, just 2 days after the Bireun earthquake, and it entered into a new eruptive phase two months later on 15 September 2013. At 252 km distance, the Bireun earthquake was the closest Mw ≥ 6 tectonic earthquake to Sinabung during the preceding year (Table 1). Seismic events at Sinabung are classified into 2 tectonic types - regional (TJ) and local earthquakes (TL) - and 4 volcanic earthquake types: VA (>1 km beneath the volcano), VB (<1 km depth), gas emission, and explosion quakes. VA seismicity was relatively high during the periods: August–March 2011, January–June 2012, and July–November 2012. The number of type-VA stayed at a low level (1–10 events/day), increased to 32 events on 4 July 2013 and reached at a peak of 129 events on 6 July (Fig. 2). Such



(a)



(b)

Fig. 2. (a) Daily number of earthquakes recorded by seismic stations monitoring Sinabung volcano. TJ: regional tectonic earthquake, TL: local tectonic, VB: shallow volcanic earthquake and VA: deep earthquake. Daily numbers of events began to be counted after the network was established on August 29th, 2010. The bottom graph shows the magnitude of tectonic events Mw ≥ 6 within 1000 km from the summit of Sinabung. The list of these tectonic events is in Table 1. (b) expanded scale plot of VA daily number for July 1st through 20 September 20, 2013.

Please cite this article as: Kriswati, E., et al., An evaluation of the possibility of tectonic triggering of the Sinabung eruption, J. Volcanol. Geotherm. Res. (2018), https://doi.org/10.1016/j.jvolgeores.2018.04.031

high seismicity was followed by the start of the new series of eruptions on 15 September 2013 (PVMBG, 2013). A more detailed summary of the seismicity at Sinabung is given in Gunawan et al. (2018).

During October 2010–July 2013, the hypocenters of VT earthquakes of Sinabung volcano were distributed within a radius of 10 km from the summit and depths from 0 to 35 km beneath the summit (Indrastuti, 2014). In July 2013, the hypocenters clustered beneath the summit and reached a depth of 8 km (Fig. 3). Hypocenters were located using Geiger Adaptive Damping (GAD) method (Nishi, 2005) with a 6 layers velocity structure, calibrated for Sinabung volcano. The layers were inferred from seismic velocities derived from a tomography study (Indrastuti, 2014).

3. Surface deformation at Sinabung volcano

Deformation at Sinabung is monitored by 4 continuous GPS stations at distances of 2 to 8 km from the summit of the volcano (Fig. 4). The GPS carrier phase data are processed using GAMIT/GLOBK (Herring et al., 2010a, 2010b, www-gpsg.mit.edu/~simon/gtgk/) to obtain loosely constrained daily solutions for the station coordinates. Daily position coordinates are calculated in the ITRF2008 reference frame using 9 IGS stations to stabilize the solution (BAKO, COCO, CNMR, DARW, DGAR, IISC, GUAM, PIMO and XMIS). Finally, we fix the location of the permanent GPS site SAMP (Sampali-Medan, North Sumatra) to define the daily positions in the Sunda block reference frame (Fig. 5).

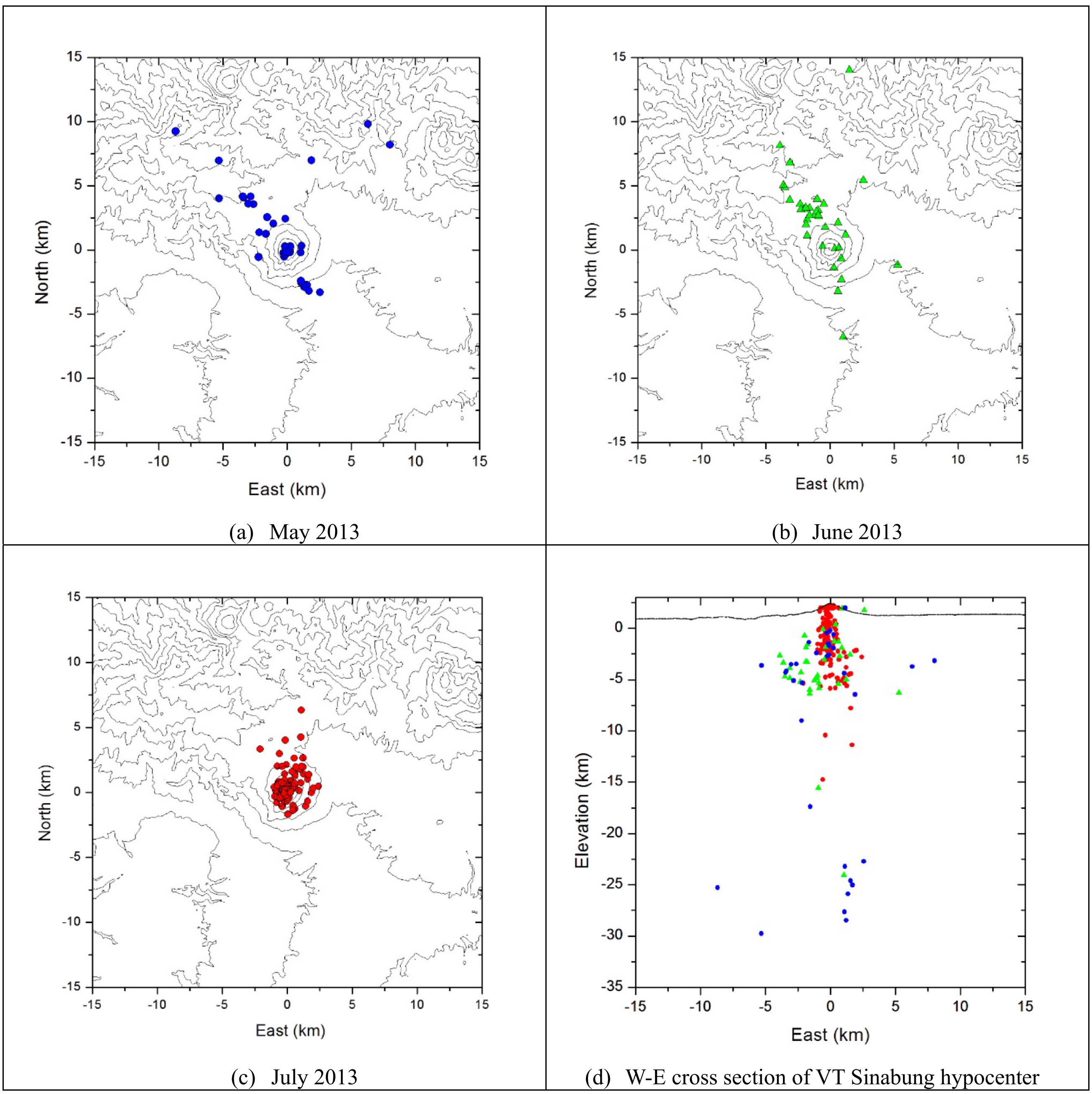


Fig. 3. Hypocenters distribution of VT earthquakes at Sinabung during May–July 2013. (a) Hypocenters located through May 26, 2013 for VT earthquakes were distributed within a radius of 10 km from the summit, (b) As in the May 2013 period, June 2013 hypocenters were distributed within a 10 km radius of the summit, (c) In July 2013, hypocenters clustered within 1 km from the summit and (d) between May and July 2013, hypocenters moved from deeper to shallower depths beneath the summit. May 2013 hypocenters shown in blue, June 2013 in green and July 2013 in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Kriswati, E., et al., An evaluation of the possibility of tectonic triggering of the Sinabung eruption, J. Volcanol. Geotherm. Res. (2018), https://doi.org/10.1016/j.jvolgeores.2018.04.031

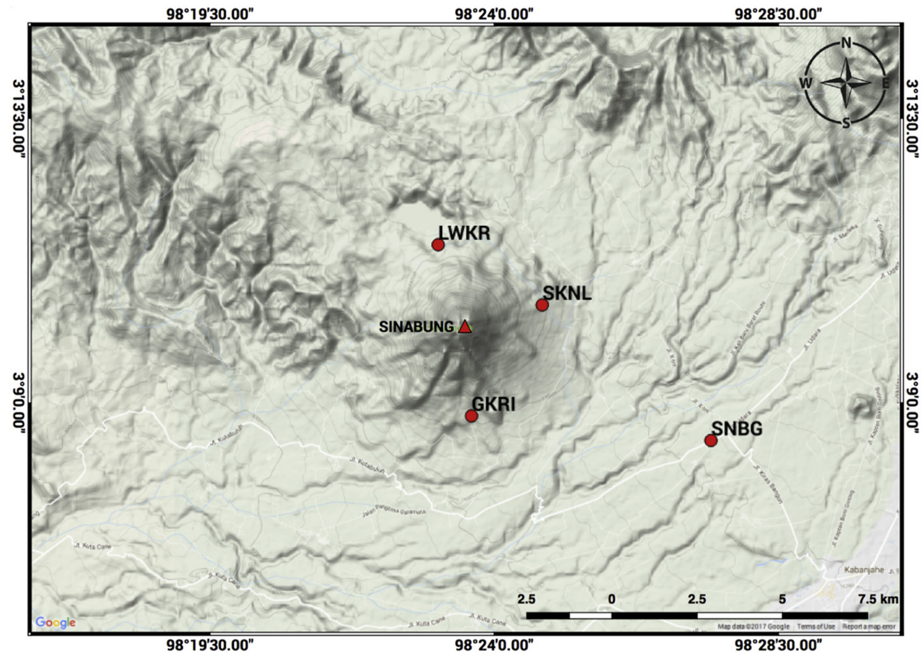


Fig. 4. Continuous GPS stations on the slope of Sinabung volcano.

Time series of GPS daily positions show that periods of decreased volcanic activity occurred during low rates of deformation and when the number of type-VA earthquakes stayed at a low level. The deformation rate changed after the Bireun earthquakes on 2 July 2013. The horizontal displacements during the 4 months after the earthquake were 8–11 mm (Kriswati et al., 2015). Specifically, there were increases in the northward components of motions at the LKWR and SKNL stations, which began within several weeks of 2 July 2013 and continued for the following several months (Fig. 5). This suggested to us that the ground deformation of the volcano might have been triggered by the Bireun Earthquake. However this could also have been related to coincidental magmatic movement at the volcano. For example, we also observed a more dramatic increase in the northward, westward and downward components and an increase in motion at the SNBG station south of the volcano, which began after the 1 December 2013 earthquake; this appears to be more directly related to magmatic intrusion (Hotta et al., 2018).

4. Strain changes due to tectonic earthquakes

As previously noted, an increase in seismicity of type-VA at Sinabung followed the Bireun by 2 days and the 2013 eruption began 2 months later on 15 September 2013. Because several other earthquakes of Mw ≥ 6 occurred in the Sumatra region but none were followed by significant volcanic unrest, we want to understand if the Bireum Earthquake was different. For this reason, we calculate the strain changes in the volcanic area forced by all of the regional tectonic earthquakes. We focus our analysis on volumetric strain, and the pattern and direction of the principal strain.

We employed seismic data and earthquake parameters from the Global CMT catalog (www.globalcmt.org/) and the U.S. Geological Survey Earthquake Hazards Program data base (earthquake.usgs.gov/) and used them to calculate the rupture area (Kanamori, 2006), rupture width, rupture length (Papazachos et al., 2004) and amount of slip (Hanks and Kanamori, 1979). Strain values and strain patterns are calculated using the equations for surface displacements due to a dislocation in an elastic half-space by Okada (1985).

The change in strain at the volcano due to the earthquake depends on the earthquake magnitude, distance of the earthquake, and the fault orientation in relation to the location of the volcano (Delle et al., 2010). At distances beyond the typical aftershock zone (~200 km for the smaller magnitude earthquakes included in this study), the static stress changes caused by earthquakes are very small compared to dynamic stress changes or other processes (Kilb et al., 2002). Thus at distances of hundreds of km between an earthquake and a volcano, a large-magnitude earthquake and a volcano that is already primed for eruption may be required to trigger an eruption by static stress change. However, the region of significant static stress change can extend to >1000 km distance from the earthquake for very large (Mw 9) earthquakes (Walter and Amelung, 2007).

In order to estimate the static strain change for earthquakes that occurred in the year preceding the 2010 and 2013 Sinabung eruptions, we conducted strain analyses for the 21 earthquakes of magnitude Mw ≥ 6 that occurred within a distance of <1000 km from Sinabung volcano in the period 2010–2013 (Table 2). The volumetric strain changes range from -3×10^{-7} to $+2 \times 10^{-7}$ and show both dilatation and compression. The results in Table 2 indicate that there is not a clear relationship between eruptive activity at Sinabung volcano and the amplitude or spatial distribution of volumetric strain in the volcanic area due to tectonic earthquakes.

Finally, we calculate the direction of the principal strain. The direction of extensional strain is in the range of 51°–126° counterclockwise from the x-axis (Table 3 and Fig. 6). Table 3 shows 5 events that have a maximum extensional strain direction perpendicular to the fault zone across Sinabung volcano.

5. Discussion

Our analysis indicates that the value of the static volumetric strain change is very small (2.84×10^{-10}) compared to the dynamic stresses that are thought to influence volcanic unrest (Manga and Brodsky, 2006) because the distance between the earthquake epicenter (252 km) and Sinabung is relatively large. Therefore, we believe that the volumetric strain factors cannot be considered as *controlling* the earthquake-volcano interaction (Table 2). We also evaluated the direction of the principal strain change from the same regional earthquakes, to determine if the strain might have *contributed to* the volcanic activity at Sinabung.

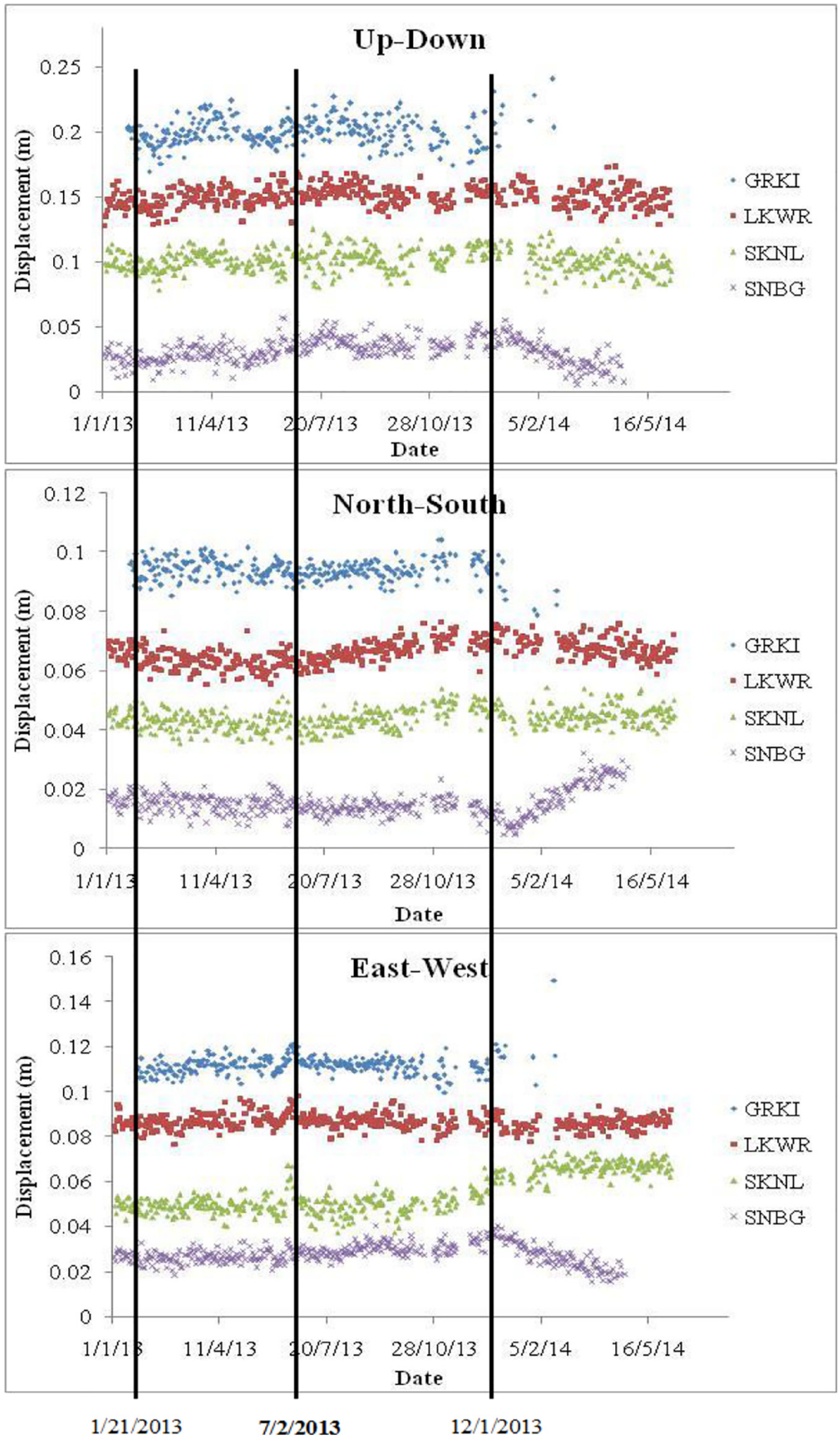


Fig. 5. Daily positions of Sinabung GPS stations relative to SAMP during the period of January 2013–May 2014. The solid lines are tectonic earthquakes during 2013 at a distances of <1000 km from Sinabung volcano and with Mw ≥ 6 (Table 1). First solid line: Sigli earthquake (21 January 2013); Second line: Bireun earthquake (2 July 2013); Third line: earthquake on the west coast of North Sumatra (1 December 2013).

Sinabung volcano is located along a fault zone associated with the northern section of the right-lateral strike-slip Sumatran fault system (SFS; McCaffrey et al., 2000). The fault plane strikes 030° where it crosses the summit of the volcano (Fig. 7). The direction of the extensional regional strain change (115°) caused by the Bireun earthquake is approximately perpendicular to the strike of the fault while the direction of the compressive strain change is nearly parallel to the fault.

We note that other earthquakes in our data set have induced the same perpendicular direction of the extensional strain change at Sinabung volcano (Tables 1 and 2). For example, the direction of extension strain change due to the 6 April 2010 earthquake is 116° (Table 2). Although precursory type-VA events were not monitored before the 2010 eruptions, we speculate that this earthquake might have contributed to triggering the 2010 eruption. Also, the earthquake of 1

Please cite this article as: Kriswati, E., et al., An evaluation of the possibility of tectonic triggering of the Sinabung eruption, J. Volcanol. Geotherm. Res. (2018), https://doi.org/10.1016/j.jvolgeores.2018.04.031

Table 2
Volumetric strain at the summit of Sinabung volcano induced by tectonic earthquakes (positive strain is compressional). The events in bold have an extensional maximum strain component perpendicular to the fault zone that transects Sinabung volcano (see Table 3).

No.	Location	Date	Mw	Distance from Sinabung (km)	Volumetric strain
1	Kepulauan Mentawai region, Indonesia	3/5/2010	6.8	823	4.98×10^{-12}
2	**Northern Sumatra, Indonesia**	**4/6/2010**	**7.8**	**173**	$\mathbf{-3.68 \times 10^{-07}}$
3	Southern Sumatra, Indonesia	5/5/2010	6.5	858	3.21×10^{-12}
4	Northern Sumatra, Indonesia	5/9/2010	7.2	271	-5.02×10^{-09}
5	**Nicobar Islands, India region**	**6/12/2010**	**7.5**	**886**	$\mathbf{1.51 \times 10^{-10}}$
	Eruption at Sinabung	8/29/2010			
6	Kepulauan Mentawai region, Indonesia	10/25/2010	6.3	716	3.57×10^{-12}
7	Kepulauan Mentawai region, Indonesia	10/25/2010	7.8	764	-1.35×10^{-09}
8	**Simeulue, Indonesia**	**1/26/2011**	**6.1**	**204**	$\mathbf{-3.59 \times 10^{-10}}$
9	Nias region, Indonesia	4/6/2011	6.0	226	-2.48×10^{-10}
10	Northern Sumatra, Indonesia	9/5/2011	6.7	60	-3.12×10^{-08}
11	off the west coast of northern Sumatra	1/10/2012	7.2	581	-1.67×10^{-09}
12	off the west coast of northern Sumatra	4/11/2012	8.2	710	-4.43×10^{-08}
13	off the west coast of northern Sumatra	4/11/2012	8.6	599	1.93×10^{-07}
14	off the west coast of northern Sumatra	4/15/2012	6.2	905	2.19×10^{-11}
15	**Northern Sumatra, Indonesia**	**6/23/2012**	**6.1**	**58**	$\mathbf{-1.58 \times 10^{-09}}$
16	Simeulue, Indonesia	7/25/2012	6.4	266	-3.16×10^{-10}
17	Kepulauan Mentawai region, Indonesia	9/14/2012	6.2	762	1.16×10^{-12}
18	47 km SSW of Sigli, Indonesia	1/21/2013	6.1	338	4.01×10^{-12}
19	**55 km S of Bireun, Indonesia**	**7/2/2013**	**6.1**	**252**	$\mathbf{-2.84 \times 10^{-10}}$
20	157 km SW of Sungai Penuh, Indonesia	7/6/2013	6.0	756	2.59×10^{-12}
	Eruption at Sinabung	9/15/2013			
21	**69 km SE of Sinabung, Indonesia**	**12/1/2013**	**6.0**	**214**	$\mathbf{-3.47 \times 10^{-10}}$

December 2013 was followed by an increase the number of deep volcanic quakes (type-VA) during the eruption (Table 2). On the other hand, other earthquakes with similar characteristics (12 June 2010, 26 January 2011 and 23 June 2012; see Table 2) have not been followed by volcanic unrest. Consequently, we infer that if the earthquakes affected Sinabung, the volcano must already be in a critical state, such that a very small strain chain could trigger volcanic activity. InSAR data indicate that Sinabung experienced magmatic intrusion during the period 2006–2009 (Chaussard and Amelung, 2012) and these data, along with the phreatic eruption of 2010, suggest that the volcano may have already reached a critical state before the earthquake.

Because unrest at Sinabung began in 2010, and occasional small volcanic earthquake swarms took place under the volcano during the relatively quiet period between 2010 and 2013, we suggest that Sinabung was already at a critical state and "primed" for eruption in 2013 when the Bireun earthquake took place. Although we cannot rule out the possibility that the beginning of the seismic unrest two days later was coincidental, we suggest that a permissive interpretation is that a small increment of extensional strain oriented perpendicular to a local fault that transects the volcano was sufficient to initiate magma ascent and the ensuing volcanic seismicity, which led to the initial 2013 eruption two months later on 15 September 2013. We point out that other authors have made similar arguments (e.g., Manga and Brodsky, 2006; Walter and Amelung, 2007) that earthquake triggering of eruptions appears to only take place in unusual situations in which the volcano in question was already pressurized and primed for

Table 3
Principal strain and direction of maximum principal strain (positive strain is compressional). The events in bold have an extensional maximum strain component perpendicular to the fault zone that transects Sinabung volcano.

No.	Date	Max_shear	Max_strain	Min_strain	Max_Direct strain direction (deg)	Min_Direct strain direction (deg)
1	3/5/2010	$1.47 \cdot 10^{-11}$	$-1.09 \cdot 10^{-11}$	$1.84 \cdot 10^{-11}$	−5.7	84.3
2	**4/6/2010**	$\mathbf{5.26 \cdot 10^{-07}}$	$\mathbf{-8.02 \cdot 10^{-07}}$	$\mathbf{2.50 \cdot 10^{-07}}$	**26.3**	**116.3**
3	5/5/2010	$4.13 \cdot 10^{-12}$	$-1.72 \cdot 10^{-12}$	$6.54 \cdot 10^{-12}$	−5.7	84.3
4	5/9/2010	$2.17 \cdot 10^{-08}$	$-2.54 \cdot 10^{-08}$	$1.79 \cdot 10^{-08}$	−31.0	59.0
5	**6/12/2010**	$\mathbf{2.54 \cdot 10^{-09}}$	$\mathbf{-2.42 \cdot 10^{-09}}$	$\mathbf{2.65 \cdot 10^{-09}}$	**36.2**	**126.2**
	Eruption at Sinabung	8/29/2010				
6	10/25/2010	$8.52 \cdot 10^{-12}$	$-5.85 \cdot 10^{-12}$	$1.12 \cdot 10^{-11}$	−10.1	79.9
7	10/25/2010	$2.45 \cdot 10^{-09}$	$-3.47 \cdot 10^{-09}$	$1.44 \cdot 10^{-09}$	0.4	90.4
8	**1/26/2011**	$\mathbf{4.56 \cdot 10^{-10}}$	$\mathbf{-7.25 \cdot 10^{-10}}$	$\mathbf{1.87 \cdot 10^{-10}}$	**25.3**	**115.3**
9	4/6/2011	$4.80 \cdot 10^{-10}$	$-6.66 \cdot 10^{-10}$	$2.94 \cdot 10^{-10}$	−39.2	50.8
10	9/5/2011	$2.11 \cdot 10^{-08}$	$-4.45 \cdot 10^{-08}$	$-2.30 \cdot 10^{-09}$	2.5	92.5
11	1/10/2012	$3.42 \cdot 10^{-09}$	$-4.67 \cdot 10^{-09}$	$2.17 \cdot 10^{-09}$	−28.1	61.9
12	4/11/2012	$4.55 \cdot 10^{-08}$	$-7.87 \cdot 10^{-08}$	$1.23 \cdot 10^{-08}$	12.9	102.9
13	4/11/2012	$3.34 \cdot 10^{-07}$	$-1.89 \cdot 10^{-07}$	$4.78 \cdot 10^{-07}$	−24.1	65.9
14	4/15/2012	$4.59 \cdot 10^{-11}$	$-2.95 \cdot 10^{-11}$	$6.23 \cdot 10^{-11}$	−29.2	60.8
15	**6/23/2012**	$\mathbf{3.35 \cdot 10^{-09}}$	$\mathbf{-4.54 \cdot 10^{-09}}$	$\mathbf{2.16 \cdot 10^{-09}}$	**21.2**	**111.2**
16	7/25/2012	$9.42 \cdot 10^{-10}$	$-1.18 \cdot 10^{-09}$	$7.05 \cdot 10^{-10}$	−15.2	74.8
17	9/14/2012	$4.02 \cdot 10^{-12}$	$-3.16 \cdot 10^{-12}$	$4.89 \cdot 10^{-12}$	−6.6	83.4
18	1/21/2013	$4.83 \cdot 10^{-10}$	$-4.80 \cdot 10^{-10}$	$4.86 \cdot 10^{-10}$	34.3	124.3
19	**7/2/2013**	$\mathbf{6.34 \cdot 10^{-10}}$	$\mathbf{-8.47 \cdot 10^{-10}}$	$\mathbf{4.20 \cdot 10^{-10}}$	**25.1**	**115.1**
20	7/6/2013	$2.40 \cdot 10^{-12}$	$-4.61 \cdot 10^{-13}$	$4.34 \cdot 10^{-12}$	−8.4	81.6
	Eruption at Sinabung	9/15/2013				
21	**12/1/2013**	$\mathbf{4.32 \cdot 10^{-10}}$	$\mathbf{-6.92 \cdot 10^{-10}}$	$\mathbf{1.72 \cdot 10^{-10}}$	**22.6**	**112.6**

Please cite this article as: Kriswati, E., et al., An evaluation of the possibility of tectonic triggering of the Sinabung eruption, J. Volcanol. Geotherm. Res. (2018), https://doi.org/10.1016/j.jvolgeores.2018.04.031

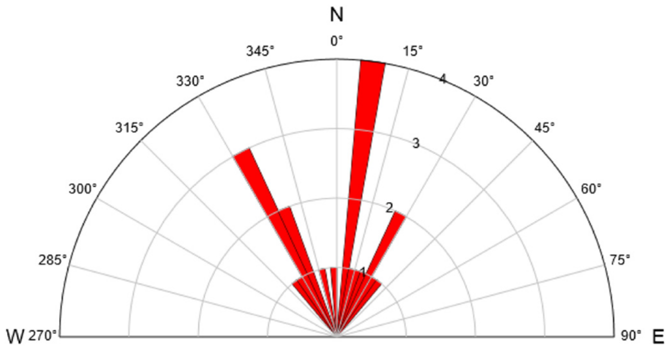


Fig. 6. Rose diagram of the direction of the extensional strain listed in Table 2. The diagram is created with 5° classes.

eruption, such that a very small change in dynamic or static strain could trigger magma ascent. Accordingly, we propose a simple conceptual model similar to that of Walter and Amelung (2007) for triggering of volcanic activity by tectonic earthquakes at Sinabung (Fig. 8).

Acknowledgements

The authors thank to The Center for Volcanology and Geological Hazard Mitigation, Geological Agency of Indonesia for opportunity to get continuous GPS data of Sinabung volcano. The continuous GPS data of Sinabung volcano was obtained from SATREPS project and we extend sincere thanks to all who gave hand to help the data collection; post observers of Sinabung volcano, Yoga E. Pamitro, Oktory Prambada, and Novianti Indrastuti. Special thanks to GREAT, ITB members, Dr. Sri Hidayati, and Maurizio Battaglia (US Geological Survay – VDAP) for valuable discussion of the manuscript. We also thank John Pallister, Stephanie Prejean and an anonymous JVGR reviewer for their constructive comments and suggestions, which improved the manuscript.

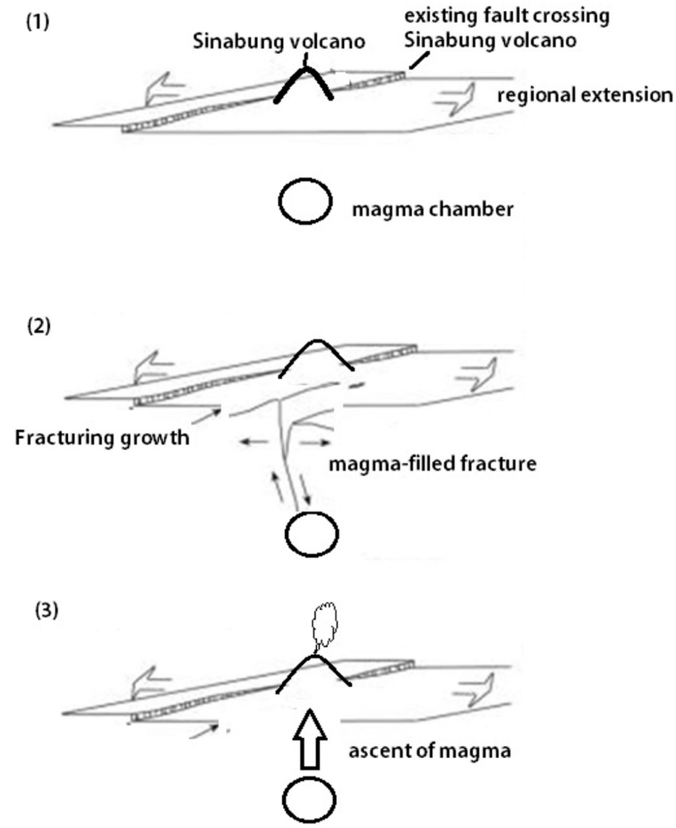


Fig. 8. Conceptual model explaining the triggering of volcanic activity by tectonic earthquakes. (1) The earthquake reactivate the fault; (2) Fault opens and magma fills the fracture, (3) Magma raises to the surface through the fracture.

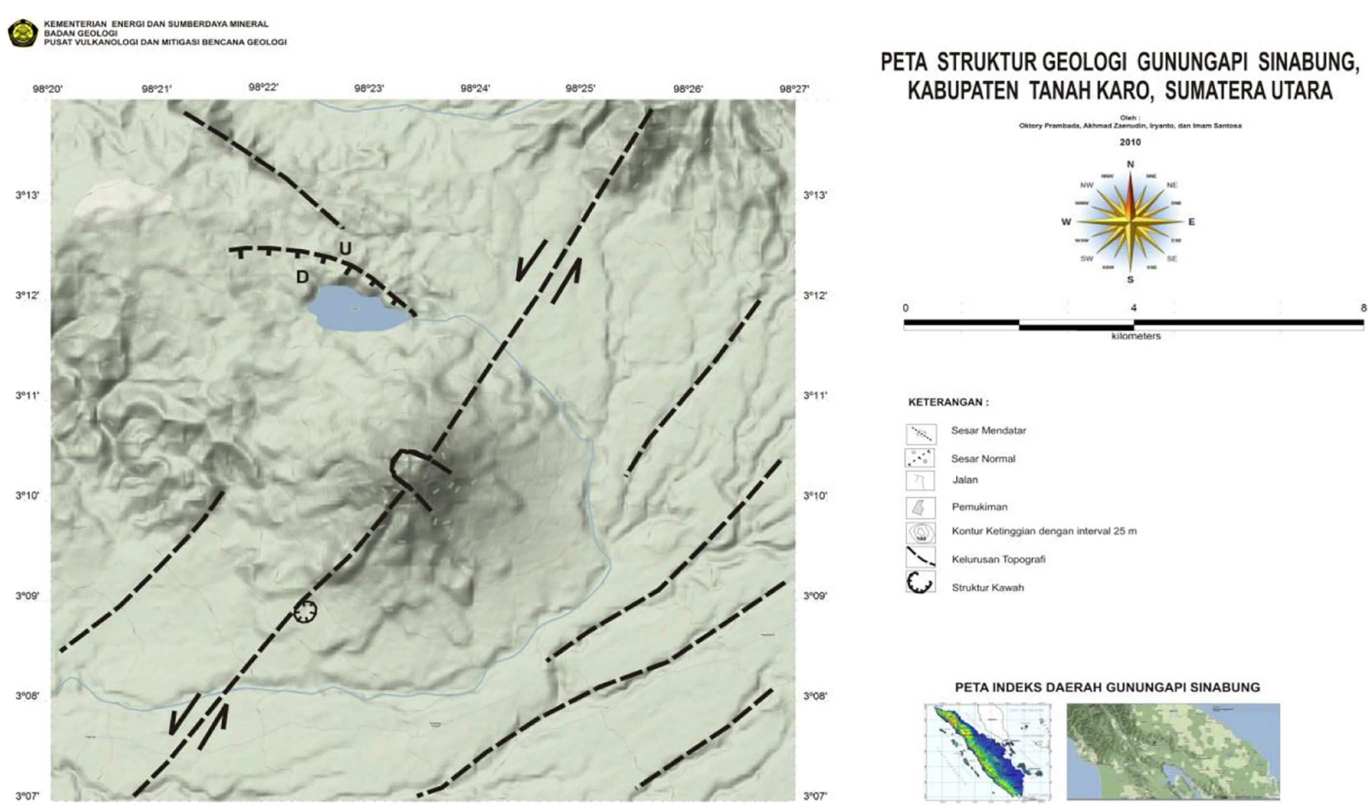


Fig. 7. Geological map of Sinabung volcano (Prambada, 2010). Black dashed line with arrow is strike slip fault across the Sinabung volcano.

References

Bursik, M., 2009. A general model for tectonic control of magmatism: examples from Long Valley Caldera (USA) and El Chichon (Mexico). Geofis. Int. 48 (1), 171–183.

Chaussard, E., Amelung, F., 2012. Precursory inflation of shallow magma reservoirs at west Sunda volcanoes detected by InSAR. Geophys. Res. Lett. 39, L21311. https://doi.org/10.1029/2012GL053817.

Delle, D.D., Harris, A.J.L., Ripepe, M., Wright, R., 2010. Earthquake-induced thermal anomalies at active volcanoes. Geology 38:771–774. https://doi.org/10.1130/G30984.1.

Dobran, F., 2001. Volcanic Processes: Mechanisms in Material Transport. Springer Science + Business Media, LLC, New York (590 pp).

Fournier, R.O., 1999. Hydrothermal processes related to movement of fluid from plastic to brittle rock in the magmatic–epithermal environment. Econ. Geol. 94, 1193–1211.

Fuchs, F., 2014. Dynamic Triggering: The Effects of Remote Earthquakes on Volcanoes, Hydrothermal Systems and Tectonics. Ph.D. Dissertation. Rheinischen Friedrich-Wilhelms-Universit at Bonn.

Gunawan, H., Surono, Budianto, A., Kristianto, Prambada, O., McCausland, W., Pallister, J., Iguchi, M., 2018. Overview of the eruptions of Sinabung eruption, 2010 and 2013–present and details of the 2013 phreatomagmatic phase. J. Volcanol. Gotherm. Res. https://doi.org/10.1016/j.jvolgeores.2017.08.005 (this issue).

Hanks, T.C., Kanamori, H., 1979. A moment magnitude scale. J. Geophys. Res. 84 (B5), 2348–2350.

Herring, T.A., King, R.W., McClusky, S.C., 2010a. GAMIT Reference Manual: GPS Analysis at MIT, Release 10.4. Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology.

Herring, T.A., King, R.W., McClusky, S.C., 2010b. Introduction to GAMIT/GLOBK, Release 10.4. Department of Earth, Atmospheric, and Planetary Sciences. Massachusetts Institute of Technology.

Hill, D.P., Prejean, S., 2007. Dynamic Triggering. In: Kanamori, H. (Ed.), Earthquake Seismology, p. 258–288, Treatise on Geophysics (Schubert, G., Ed. in chief). 4. Elsevier, Amsterdam.

Hill, D.P., Johnston, M.J.S., Langbein, J.O., Bilham, R., 1995. Response of Long Valley Caldera to the mw = 7.3 landers, California earthquake. J. Geophys. Res. 100, 12985–13005.

Hill, D.P., Pollitz, F., Newhall, C., 2002. Earthquake-volcano interactions. Phys. Today 55 (11), 41–47.

Hotta, K., Iguchi, M., Ohkura, T., Gunawan, H., Rosadi, U., Kriswati, E., 2018. Magma intrusion and effusion at Sinabung volcano, Indonesia, from 2013 to 2016, as revealed by continuous GPS observation. J. Volcanol. Geotherm. Res. https://doi.org/10.1016/j.jvolgeores.2017.12.015 (this issue).

Indrastuti, N., 2014. Studi Kegempaan Dan Seismik Tomografi Gunung Sinabung (Earthquake and seismic tomography of Sinabung volcano). M.Sc. Thesis. Earth Science Program, Institute of Technology, Bandung, pp. 72–76.

Kanamori, H., 2006. Lessons from the 2004 Sumatra–Andaman earthquake. Philos. Trans. R. Soc. Lond. A 364:1927–1945. https://doi.org/10.1098/rsta.2006.1806 (published online 27 June 2006).

Kilb, D., Gomberg, J., Bodin, P., 2002. Aftershock triggering by complete Coulomb stress changes. J. Geophys. Res. 107. https://doi.org/10.1029/2001JB000202.

King, G.C.P., Stein, R.S., Lin, J., 1994. Static stress changes and the triggering of earthquakes. Bull. Seismol. Soc. Am. 84, 935–953.

Kriswati, E., Meilano, I., Yunazwardi, M., Abidin, H.Z., Pamitro, Y.Y., 2012. Preliminary Study of interaction system between Talang volcanic activity and regional tectonics of West Sumatera. American Geophysical Union, Fall Meeting 2012, Abstract Id. T43A-2645.

Kriswati, E., Kuncoro, H., Meilano, I., 2015. Low rate of Sinabung deformation inferred by GPS measurement. Am. Inst. Phys. Conf. Proc. 1658, 050007. https://doi.org/10.1063/1.4915046.

Manga, M., Brodsky, E.E., 2006. Seismic triggering of eruptions in the far field: volcanoes and geysers. Annu. Rev. Earth Planet. Sci. 34, 263–291.

McCaffrey, R.P., Zwick, Y., Bock, L., Prawirodirdjo, J., Genrich, S.S., Puntodewo, O., Subarya, C., 2000. Strain partitioning during oblique plate convergence in northern Sumatra: geodetic and seismologic constraints and numerical modeling. J. Geophys. Res. 105, 28,363–28,376.

Nakamura, K., 1975. Volcanic eruption caused by squeeze up of magma due to compressive tectonic stress. Kasan = Bull. Volc. Soc. Japan 20 (2), 116.

Nishi, K., 2005. Hypocenter Calculation Software GAD (Geiger's Method with Adaptive Damping), ver.1, JICA report - May 2005.

Nostro, C., Stein, R.S., Cocco, M., Belardinelli, M.E., Marzocchi, W., 1998. Two-way coupling between Vesuvius eruptions and southern Apennine earthquakes, Italy by elastic stress transfer. J. Geophys. Res. 103 (B10), 24,487–24,504.

Okada, Y., 1985. Surface deformation due to shear and tensile faults in a half-space. Bull. Seismol. Soc. Am. 75 (4), 1135–1154.

Papazachos, B.C., Scordilis, E.M., Panagiotopoulos, D.G., Papazachos, C.B., Karakaisis, G.F., 2004. Global relations between seismic fault parameters and moment magnitude of earthquakes. Bull. Geol. Soc. Greece 36, 1482–1489.

Prambada, O., 2010. Laporan Pemetaan G. Sinabung, (Geologic mapping report on Sinabung volcano). Pusat Vulkanologi dan Mitigasi Bencana Geologi, Bandung, Indonesia.

Purbawinata, M.A., 2005. Peningkatan kegiatan G. Talang, Kab. Solok, Sumatra Barat (Increased activity at Talang volcano, Solok Regency, West Sumatra). Direktorat Vulkanologi dan Mitigasi Bencana Geologi, Bandung, Indonesia.

PVMBG (Pusat Vulkanologi dan Mitigasi Bencana Geologi), 2013. Peningkatan Status G. Sinabung Dari Waspada Menjadi Siaga, 15 September 2013 (Upgrade to status of Sinabung Volcano from Alert to Standby alert level, 15 September, 2013). http://vsi.esdm.go.id/index.php/gunungapi/aktivitas-gunungapi/230-peningkatan-status-g-sinabung-dari-waspada-menjadi-siaga-16-september-2013.

Stein, R.S., 1999. The role of stress transfer in earthquake occurrence. Nature 402, 605–609.

Walter, T.R., Amelung, F., 2006. Volcano-earthquake interaction at Mauna Loa volcano, Hawaii. J. Geophys. Res. 111, B05204. https://doi.org/10.1029/2005JB003861.

Walter, T.R., Amelung, F., 2007. Volcanic eruptions following $M \geq 9$ megathrust earthquakes: implications for the Sumatra-Andaman volcanoes. Geology 35, 539–542.

White, R.A., Harlow, D.H., 1993. Destructive upper-crustal earthquakes of Central America since 1900. Bull. Seismol. Soc. Am. 83, 1115–1142.